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MESSAGE

REF: Contract F61775-98-WEO49

Dear Dr. Stickley,
Please find enclosed the final report.

Sincerely,

T Erneux
Thomas Erneux

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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking Ujiversite Libre de Bruxelles; Optique Nonlineaire Theorique as follows: The contractor will investigate predictions of the semiconductor laser equations for large values of the detuning parameter in an effort to understand instabilities in the laser's output intensity that have been observed by AFRL scientists.

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Final Report for the contract F61775-98-WEO49
entitled "Semiconductor laser instabilities"
by Thomas Erneux

Semiconductor lasers (SLs) have a wide range of applications but a weak optical feedback is enough to destabilize its normal output. These instabilities are generating higher intensity or frequency noise which are undesirable for certain applications. In close collaboration with the Nonlinear Optics group at Kirtland AFB, Dr. Erneux has proposed to apply new asymptotic techniques for solving the laser equations. These techniques allow us to determine analytical expressions for all bifurcation points.

The simplest problem that models the interactions between a SL and the outside world is the laser subject to optical injection. It is formulated by three equations for the amplitude of the electrical field, $|E| = 1 + \alpha$, the phase difference between master and slave electrical fields, ψ, and the carrier density above threshold, Z

$$\frac{d\alpha}{ds} = Z(1+\alpha) + \eta\cos(\psi), \quad (1)$$

$$\frac{d\psi}{ds} = \Omega - bZ - \frac{\eta}{1+\alpha}\sin(\psi), \quad (2)$$

$$T\frac{dZ}{ds} = -Z\left(1 + 2P(1+\alpha)^2\right) - P(2\alpha + \alpha^2). \quad (3)$$

In these equations, time is $s \equiv t/\tau_p$ where τ_p is the photon lifetime. Ω denotes the detuning between the frequency of the master laser and the free-running slave laser. P is the pumping current above threshold. $\eta > 0$ is the injection rate. $T \equiv \tau_s/\tau_p$ is defined as the ratio of the carrier and photon lifetimes. b is the linewidth enhancement factor b. Typical values of P, Ω, η, T and b are $P \sim 0.1 - 1$, $\Omega \sim 0.01$, $\eta \sim 0.01$, $T \sim 10^3$ and $b \sim 4 - 6$. The small value of η implies that the amplitude of the electrical field is close to its value at $\eta = 0$ (i.e., $|E| = 1$) and motivates the decomposition $|E| = 1 + \alpha$. The basic time of the laser oscillations is the laser relaxation oscillations frequency $\omega = \sqrt{2P/T}$.

Recent experiments have suggested that there exists a domain of bistability at large negative values of the detuning. This bistability corresponds to

the coexistence of stable pulsating intensity regimes and stable steady states. The main objective of our analysis was to understand analytically the mechanism leading to this coexistence. To this end, we have considered the limit of large detunings (specifically, the limit $|\Delta| = |\Omega/\omega| = O(b)$, $\Lambda = \eta/\omega = O(b)$ as $b \to \infty$ of Eqs. (1)-(3)).

At a fixed negative Δ and changing Λ from zero, we find that this domain of bistability is bounded below by a steady state limit point and above by a bifurcation point to quasiperiodic oscillations located at $\Lambda = \Lambda_{QP}$ defined by [1]

$$\Lambda_{QP} \equiv \sqrt{-\frac{\xi}{b}\Delta^3} \ (\Delta < 0). \tag{4}$$

where $\xi \equiv \frac{\omega}{2P}(1+2P) << 1$ is defined as the damping rate of the laser relaxation oscillations. Λ_{QP} is a bifurcation point from the multi-wave mixing regime to quasiperiodic oscillations. In the second part of our activities at Kirtland, we investigate how $\Lambda_{QP}(\Delta)$ behaves as Δ is progressively increased. We analyze Eqs. (1)-(3) by a new perturbation analysis valid for arbitrary $\Delta = O(1)$ but small Λ. Away from the resonance points $\Delta = 0, \pm 1, \pm 2, ..$, the basic multi-wave mixing regime (frequency $\sigma = |\Delta|$) exhibits a bifurcation to quasiperiodic oscillations (frequencies $\sigma_1 = |\Delta|$ and $\sigma_2 \simeq 1$) which is located at

$$\Lambda_{QP} \equiv \sqrt{\frac{\xi}{b}\Delta(1-\Delta^2)} \ \left(\Delta(1-\Delta^2) \geq 0\right). \tag{5}$$

Note that (5) is matching the expression (4) for large negative Δ and thus (5) is the natural continuation of (4) as $|\Delta|$ becomes $O(1)$. Near the resonant point $\Delta = 0$, ± 1, ± 2, ... special analyses are needed because the quasiperiodic oscillatioons may lock into multi-periodic oscillations. Figure 1 represents the stability diagram of the steady states in the Λ vs Δ diagram (the values of the parameters are $P = 0.5$, $b = 5$ and $T = 1000$). The locking domain corresponds to the domain $\Lambda \geq \Lambda_{LP}$ (Λ_{LP} is defined as the limit point of the steady states). The steady states are however unstable in the region bounded by the curve $\Lambda = \Lambda_H$ (Λ_H is defined as a stable Hopf bifurcation point). The domain below the two straight lines $\Lambda = \Lambda_{LP}$ correspond to the multi-wave mixing regime. Both the multi-wave mixing solution and the Hopf bifurcation solution lead to pulsating intensity oscillations but are characterized by an unbounded and a bounded phase ψ, respectively. $\Lambda = \Lambda_{QP}$ corresponds to a bifurcation point from the multi-wave mixing regime to

quasiperiodic oscillations and is defined by (5).

We have considered both a case of negative Δ and a case of positive Δ. According to our analysis, a bifurcation to quasiperiodic oscillations should be observed for Δ slightly less than -1 for Λ not too large. Figure 2 shows the numerical bifurcation diagram of the periodic and quasiperiodic solutions exhibiting the bifurcation points $\Delta_{PD} \simeq -1.61$ (analytical approximation: $\Delta_{PD} \simeq -1.5$) and $\Delta_{QP} \simeq -1.24$ (analytical approximation: $\Delta_{QP} \simeq -1.35$). The values of the parameters are $P = 0.5$, $b = 5$, $T = 2000$ and $\Lambda = 0.1$.

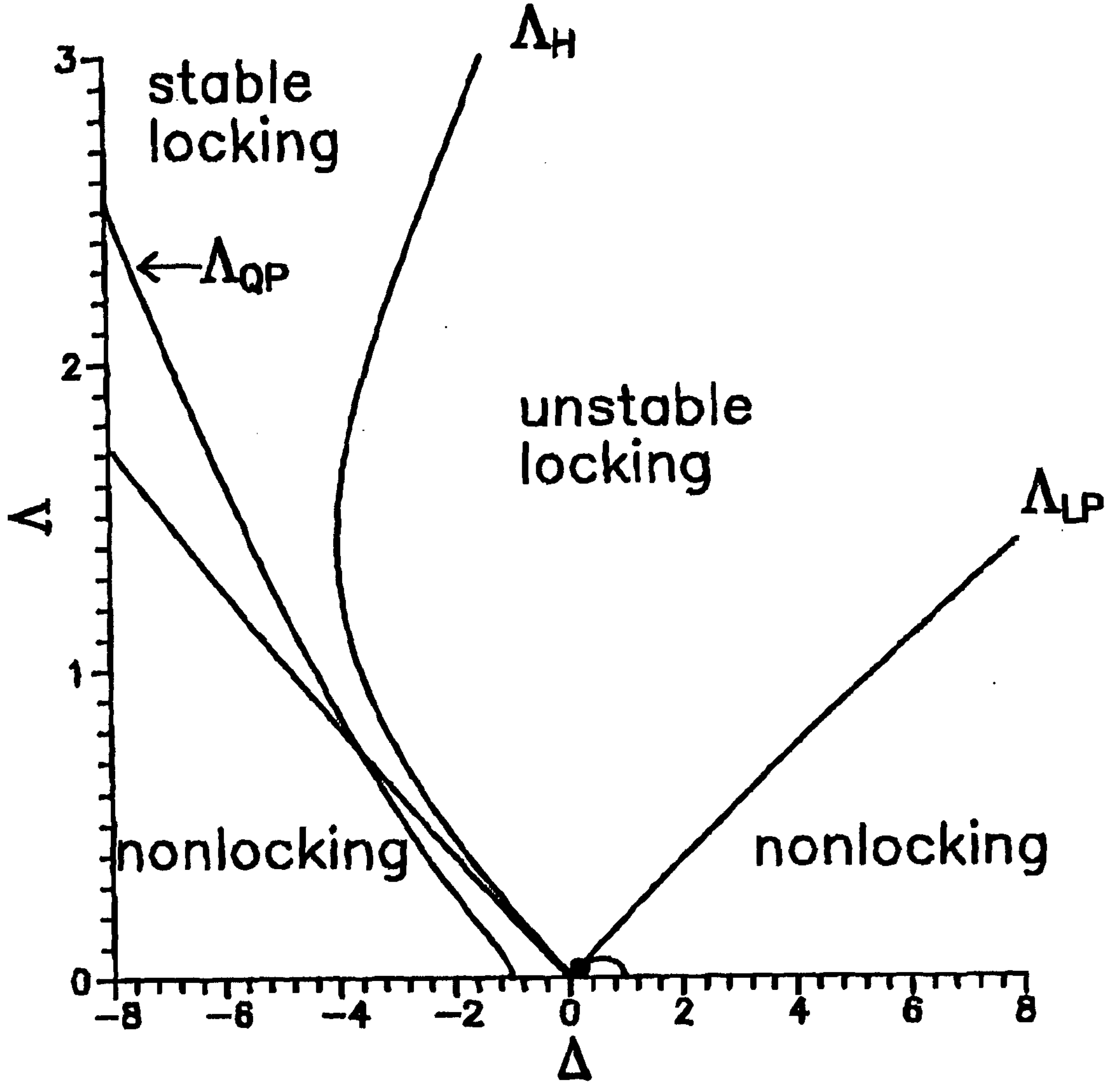
We next examine a case of positive detuning and determine the bifurcation diagram in terms of Λ for a fixed value of Δ close to zero. Figure 3 shows the quasiperiodic bifurcation which appears soon as Λ increases from zero. The straight lines represent the maximum and the minimum of the small amplitude multi-wave mixing regime given by $\alpha = \pm\Lambda\Delta/(1-\Delta^2)$. The values of the parameters are $P = 0.5, b = 5, T = 1000$ and $\Delta = 0.25$. Note that the analytically estimated value for the quasiperiodic bifurcation point, $\Lambda_{QP} \simeq 0.44$, compares well with the numerically estimated value, $\Lambda_{QP} \simeq 0.42$.

References

[1] V. Kovanis, T. Erneux and A. Gavrielides, Largely detuined injection-locked semiconductor lasers, Opt. Comm. **159**, 177-183 (1999).

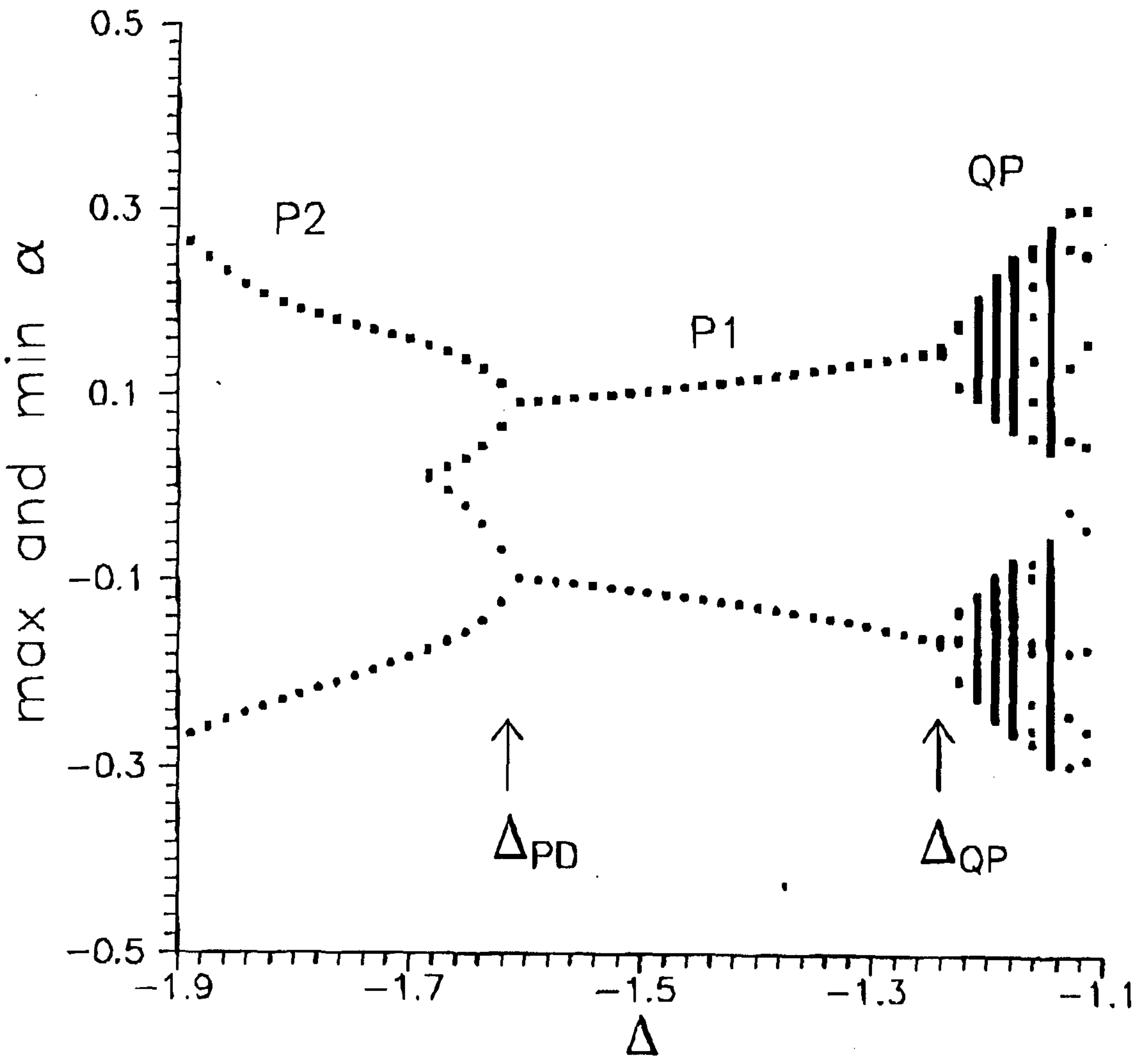
[2] M. Nizette, T. Erneux, A. Gavrielides and V. Kovanis, Injection locked semiconductor laser dynamics from large to small detunings, in Physics and Simulations of Optoelectronic Devices VII, W.W. Chow, M. Osinski, Eds., Proc. SPIE **3625**, to appear (1999)

Figure 1



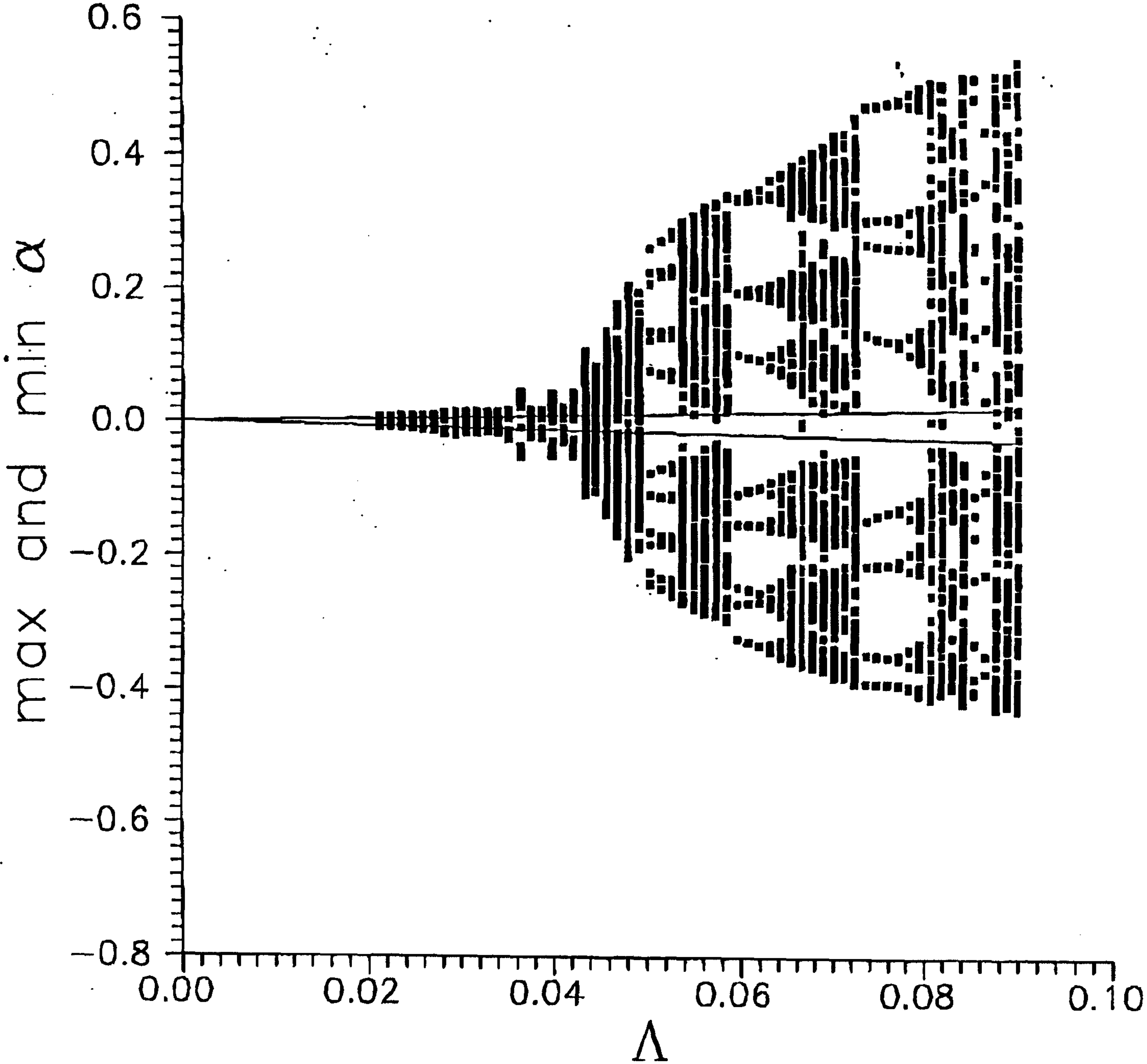
stable
locking
Λ_H
Λ_{QP}
unstable
locking
Λ_{LP}
nonlocking
nonlocking
Λ
Δ
3
2
1
0
−8
−6
−4
−2
0
2
4
6
8

Figure 2



max and min α
0.5
0.3
0.1
−0.1
−0.3
−0.5
−1.9
−1.7
−1.5
−1.3
−1.1
Δ
P2
P1
QP
Δ_{PD}
Δ_{QP}

Figure 3



max and min α
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
0.00
0.02
0.04
0.06
0.08
0.10
Λ